Received 2001 October 11; accepted 2001 November 6
Preprint typeset using LaTeX style emulateapj v. 14/09/00

DARK MATTER HALOS AROUND ELLIPTICAL GALAXIES: HOW RELIABLE IS THE STELLAR KINEMATICAL EVIDENCE?

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Received 2001 October 11; accepted 2001 November 6

ABSTRACT

Hierarchical models of galaxy formation and various observational evidence suggest that elliptical galaxies are, like disk galaxies, embedded in massive dark matter halos. Stellar kinematics are considered the most important tracer for this dark halo at a few effective radii. Using detailed modeling techniques, several authors have recently presented stellar kinematical evidence of a dark halo for a number of elliptical galaxies. In these modeling techniques, dust attenuation (absorption and scattering of starlight by dust grains) has not been taken into account. Nevertheless, elliptical galaxies contain a significant amount of interstellar dust, which affects all observable quantities, including the observed kinematics. We constructed a set of dynamical models for elliptical galaxies, in which dust attenuation is included through a Monte Carlo technique. We find that a dust component, shallower than the stellar distribution and with an optical depth of order unity, affects the observed kinematics significantly, in the way that it mimics the presence of a dark halo. If such dust distributions are realistic in elliptical galaxies, we are faced with a new mass-dust degeneracy. Taking dust attenuation into account in dynamical modeling procedures will hence reduce or may even eliminate the need for a dark matter halo at a few effective radii.

Subject headings: dark matter — dust, extinction — galaxies: elliptical and lenticular, cD — galaxies: halos — galaxies: kinematics and dynamics

1. INTRODUCTION

It has been generally accepted for decades that disk galaxies are ubiquitously embedded in massive dark matter halos. During the past few years, a consensus has been developing that elliptical galaxies also contain dark halos. Their existence is predicted by hierarchical theories of galaxy formation, and has recently been supported by various observational evidence, such as gravitational lensing (Griffiths et al. 1996; Keeton, Kochanek, & Falco 1998) and X-ray measurements of their hot gas atmospheres (Matsushita et al. 1998; Loewenstein & White 1999). Although useful to infer the large-scale mass distribution of elliptical galaxies, these observations do not sufficiently constrain the detailed structure of the mass distribution at a few effective radii. This region is particularly important for understanding the coupling of the dark and luminous matter. In order to constrain the gravitational potential at these radii, other, kinematical, tracers are used. For disk galaxies, the neutral hydrogen gas, which radiates at 21 cm, forms an excellent kinematical tracer; elliptical galaxies, however, usually lack the necessary amounts of interstellar gas. Discrete tracers such as planetary nebulae, globular clusters and dwarf satellite galaxies can be used (Zepf et al. 2000; Romanowski & Kochanek 2001; Kronawitter et al. 2000), but due to their small numbers and larger distances to the center, they do not sufficiently constrain the gravitational potential at a few R_e. This leaves stars as the main tracer for the mass distribution in elliptical galaxies in this region.

The first stellar kinematical evidence for dark matter halos around elliptical galaxies came in the early 1990s. At that time, the available kinematical data consisted of the mean projected velocity $\langle v_p \rangle$ and the projected velocity dispersion σ_p, at projected radii rarely larger than $1R_e$. For a number of elliptical galaxies, the projected velocity dispersion profile was found to decrease only slowly with projected radius, a behavior that was interpreted as a signature for the presence of a dark matter halo (Saglia, Bertin, & Stiavelli 1992; Saglia et al. 1993). However, such σ_p profiles can also be generated by intrinsically tangentially anisotropic galaxy models, without the need for dark matter halos. The velocity dispersion profile alone does not contain sufficient kinematic information to constrain both the mass and the orbital structure of elliptical galaxies, a problem usually referred to as the mass-anisotropy degeneracy (Gerhard 1993). This degeneracy can be broken by considering the higher order kinematical information contained in the line-of-sight velocity distributions (LOSVDs), usually parameterized by means of the Gauss-Hermite shape parameters h_i (where $i \geq 3$; Gerhard 1993; van der Marel & Franx 1993). In particular, the additional information contained in the h_4 profile provides the key to breaking the mass-anisotropy degeneracy: the combination of a slowly decreasing velocity dispersion profile, together with a relatively large h_4 profile, is generally interpreted as evidence for a dark matter halo.[2] Thanks to improved instrumentation and data reduction techniques, it is nowadays possible to determine $\langle v_p \rangle$, σ_p, h_3 and h_4 profiles with a reasonable accuracy, out to several R_e. Several authors have recently adopted such kinematical in-

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[2] For a detailed analysis of the effects of mass and anisotropy on the projected dispersion and h_4 profiles, we refer to section 3 of Gerhard et al. (1998).

formation to constrain the dark matter distribution in a number of elliptical galaxies (Rix et al. 1997; Gerhard et al. 1998; Saglia et al. 2000; Kronawitter et al. 2000).

In this entire discussion, it has (implicitly) been assumed that elliptical galaxies consist of two dynamically important components: the stars moving as test particles in a gravitational potential, generated by both stellar and dark mass. During the past decade, it has become well established that elliptical galaxies also contain a surprisingly large amount of interstellar dust (up to several million solar masses), most of it believed to be distributed diffusely over the galaxy (Roberts et al. 1991; Goudfrooij & de Jong 1995; Bregman et al. 1998). This number must be revised an order of magnitude upward, if more detailed dust mass estimators (Merluzzi 1998) or additional submillimeter measurements (Fich & Hodge 1993; Wiklind & Henkel 1995) are taken into account. This is still a negligible fraction of the total mass of the galaxy, such that the dust will hardly influence the gravitational potential. Nevertheless, it has a significant role in galaxy dynamics: dust grains efficiently absorb and scatter optical photons. Interstellar dust will therefore affect all observable quantities, including the observed kinematics.

We are undertaking an effort to understand the impact of interstellar dust on the observed kinematics in elliptical galaxies. Previously, we investigated how absorption by dust grains affects the light profile and the observed kinematics (Baes & Dejonghe 2000; Baes, Dejonghe, & De Rijcke 2001). We found that the observed kinematics are affected only in the most central regions, the magnitude of these effects being of the order of a few percents. Here we have extended our modeling to incorporate the process of scattering off dust grains. We will show in this Letter that this has a considerable effect on the observed kinematics, in particular concerning the stellar kinematical evidence for dark matter halos.

2. THE MODELING

To investigate the effects of attenuation[3] on the observed kinematics, we constructed a spherically symmetric elliptical galaxy model, consisting of a stellar and a dust component. For the stellar distribution, we adopted an isotropic Hernquist model. It is a reasonable approximation for the observed surface brightness distribution of elliptical galaxies, and has the advantage that most of the internal stellar kinematics can be calculated analytically (Hernquist 1990). The distribution of the (diffuse) dust in elliptical galaxies is not well constrained; its presence has been demonstrated only indirectly. We adopted a dust distribution that is shallower than the stellar density, with a total visual optical depth of order unity. Such a model seems to be indicated by the observed color gradients in elliptical galaxies (Witt et al. 1992; Goudfrooij & de Jong 1995; Wise & Silva 1996). For the optical properties of the dust grains (the relative opacity, the scattering albedo, and the phase function), we adopted the values calculated by Maccioni & Perinotto (1994) and displayed in Di Bartolomeo, Barbaro & Perinotto (1995). A more extended set of models, with a larger variety in optical depth and star-dust geometry, will be presented in a forthcoming paper (M. Baes & H. Dejonghe, 2001, in preparation).

The inclusion of dust absorption in the calculation of the LOSVDs was rather straightforward: it required an extra factor in the integration along the line of sight (Baes & Dejonghe 2000). If scattering is included, however, such an approach is not possible anymore. Indeed, photons can now leave their initial path, and reach the observer through a completely different path. Therefore, we adopted a Monte Carlo technique to include this process. Basically, the method consists of following the individual path of a very large number of photons (typically about 10^7), selected randomly from phase space, according to the phase space distribution function of the galaxy. Knowledge of the path along which each photon leaves the galaxy, together with the kinematical signature of the star that emitted it, enables us to construct the surface brightness profiles and LOSVDs of the galaxy, both with and without dust attenuation taken into account. The σ_p and h_4 profiles are extracted from the LOSVDs (the $\langle v_p \rangle$ and h_3 profiles are identically zero, because we consider a spherically symmetric nonrotating galaxy model). A more detailed description of the method will be given in M. Baes & H. Dejonghe (2001, in preparation).

A check on the method was provided by the case where only absorption is taken into account: we found the results of the Monte Carlo simulation to be in perfect agreement with our previously obtained semianalytical results (Baes & Dejonghe 2000).

3. THE OBSERVED KINEMATICS

In Figure 1, the effect of dust attenuation on the observed kinematics is illustrated. For the lines of sight that pass near the galaxy center, the kinematics are nearly unaffected. Because of the modest (and conservative) dust masses we used, the high-velocity stars in the galaxy center are only slightly obscured. As a result, the velocity dispersion only decreases marginally. At large radii, however, the kinematics are seriously affected. The σ_p profile drops less steeply, and the h_4 parameter is significantly larger compared to the dust-free case. In Figure 2, we show the LOSVD at $R = 5R_e$ of our galaxy model, with and without dust attenuation. This figure clearly indicates that dust attenuation brings on significant high-velocity wings in the outer LOSVDs. In particular, it should be noted that these LOSVDs do not vanish at the local escape velocity: hence, stars are observed that can physically not be present on these lines of sight. These wings are a scattering effect, as demonstrated in Figure 3, and they are responsible for the increase of σ_p and h_4. Attenuation by interstellar dust apparently has a kinematical signature that is strikingly similar to the presence of a dark matter halo: a velocity dispersion profile that decreases more slowly than expected, and a relatively large h_4 profile. Hence, dust-affected kinematics mimic the presence of a dark matter halo.

4. MODELING THE DUST-AFFECTED KINEMATICS

To check this into more detail, we considered our dust-affected kinematics as an observational data set, and modeled it as any dynamical modeler would do, i.e., without taking dust attenuation into account. We concentrated on

[3] We will refer to attenuation as the combined effect of absorption and scattering

the model with $\tau_V = 1$, and considered a data set consisting of the K-band photometry and V-band σ_p and h_4 profiles, out to $5R_e$. The modeling was performed with a powerful non-parametric modeling technique based on quadratic programming (Dejonghe 1989).

4.1. *Models with a constant M/L*

First, we tried to find out whether the data were consistent with a model with a constant M/L. We constructed a set of dynamical models, with M/L as a free parameter. The best-fitting model is represented by the dashed line in Figure 4. Obviously, this fit is not satisfactory: it can fit the σ_p profile, but only through a strong tangential anisotropy, reflected in a strongly negative h_4 profile. It is impossible to fit both the σ_p and h_4 profiles with a constant M/L model.

4.2. *Models with a dark matter halo*

In order to construct models with a rising M/L, i.e. with a dark halo, we considered a set of Hernquist potentials, each with a different scale length. We constructed a set of dynamical models, with both the potential scale length and the mass-to-light ratio as free parameters. The best fit to the photometry and the σ_p and h_4 profiles[4] is plotted in solid lines in Figure 4. Its potential has a scale length 45% larger than the original Hernquist potential, and in the maximum stellar mass hypothesis (the analogue for the maximum disk hypothesis in disk galaxies), the dark matter contributes roughly a third of the total mass within $1\,R_e$, and half of the total mass within the last data point. This clearly demonstrates that the effects of dust attenuation can mimic the presence of a dark matter halo. Taking dust attenuation into account in dynamical modeling procedures will hence reduce or may even eliminate the need for a dark matter halo at a few R_e.

5. CONCLUSIONS

In view of these results, we may have to reconsider the stellar kinematical evidence for dark matter halos. In analogy with the mass-anisotropy degeneracy, which could be lifted by considering higher-order shape parameters for the LOSVDs, we are now faced with a new degeneracy, which could be called the mass-dust degeneracy. Indeed, the attenuation (in particular the scattering) by dust grains has the same effect on the stellar kinematics as a dark matter halo. At least, these results apply for the model we have explored in this Letter, with a dust distribution shallower than the stars and with an optical depth $\tau_V = 1$. We are well aware that these assumptions are quite uncertain, and an extended set of models, with a large variety in optical depth and star-dust geometry, is being investigated.

The new mass-dust degeneracy strongly complicates the use of stellar kinematics as a tracer for the mass distribution in elliptical galaxies. Although the presence of dark matter halos nowadays seems firmly established at very large scales, this leaves us with a major problem concerning the determination of the dark halo properties at a few effective radii. There are two possible ways to break this new degeneracy. The first option is to observe the kinematics at near-infrared wavelengths, where the effects of dust are negligible. This, however, poses a serious observational challenge in the off-center regions. The second option is to include radiative transfer calculations in dynamical modeling techniques. Besides a computational challenge, this requires a better knowledge of the spatial distribution and of the optical properties of dust grains in elliptical galaxies than we have today. The new generation of far-infrared and submillimeter instruments, such as ALMA and *SIRTF*, will help to solve this problem.

The authors would like to thank T. van Albada and A. N. Witt for stimulating discussions, and the referee, N. Cretton, for his constructive remarks. M. B. acknowledges the financial support of FWO-Vlaanderen.

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[4] The slight disagreement at the center of the h4 profile is unimportant, as we are primarily interested in the outer regions.

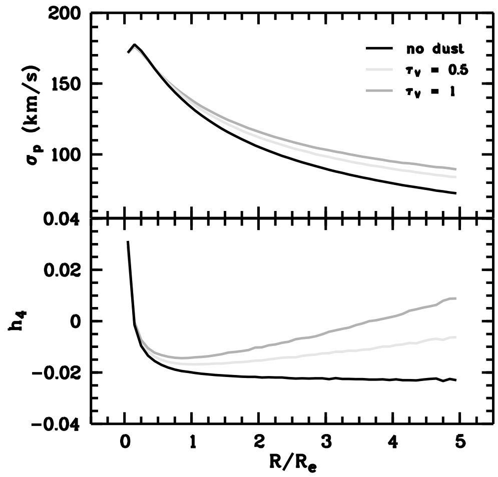

FIG. 1.— Effect of dust attenuation on the projected kinematics, in particular the σ_p and the h_4 profiles. The profiles are shown for a model without dust attenuation and for models with optical depths of $\tau_V = 0.5$ and $\tau_V = 1$.

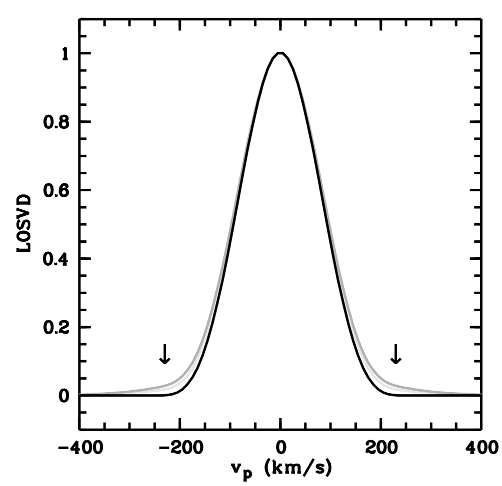

FIG. 2.— Effect of dust attenuation on the outer LOSVDs. Shown is the LOSVD at $R = 5R_e$; the different curves correspond to those in Fig. 1. The LOSVDs are normalized to unity at $v_p = 0$. The escape velocity $v_{\rm esc}$ at this line of sight is indicated by an arrow. If dust attenuation is not taken into account, no stars are observed with line-of-sight velocities larger than $v_{\rm esc}$. If dust attenuation is considered, however, the LOSVD does not vanish at $v_{\rm esc}$.

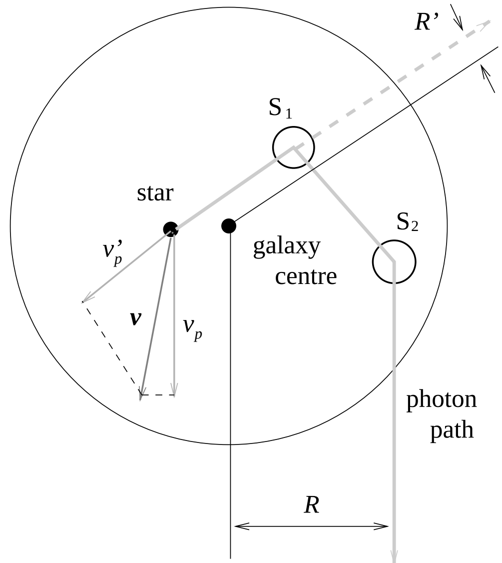

Fig. 3.— Scattering as the reason for the high velocity wings in the outer LOSVDs. A photon is emitted by a star near the galaxy center, which has an intrinsic velocity $\boldsymbol{v}$. If there were no dust attenuation, the photon would travel along a straight line, and contribute a line-of-sight velocity v'_p to the LOSVD at the projected radius R'. In a dusty galaxy, however, photons can leave their initial path and reach the observer through a completely different path. In the figure, the photon is scattered twice, at S_1 and S_2, and it leaves the galaxy along a line of sight with projected radius R. During its journey through the galaxy, the photon carries along the kinematical signature of the star that emitted it. Hence, it will contribute the line-of-sight velocity v_p to the LOSVD at the line of sight R. In particular, it is possible that the observed line-of-sight velocity v_p exceeds the local escape velocity $v_{\rm esc}(R)$. This is indeed observed in the outer LOSVDs: they do not vanish at the local escape velocity (Fig. 2).

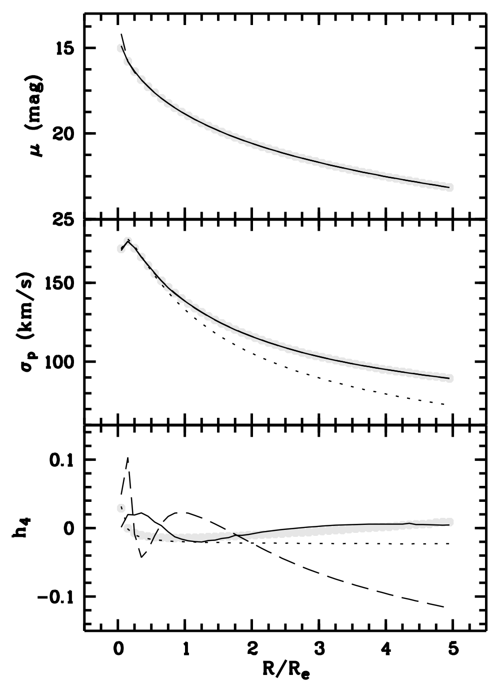

Fig. 4.— Two fits to the photometric and kinematical data corresponding to the model with optical depth $\tau_V = 1$. Shown are the surface brightness μ, velocity dispersion σ_p, and h_4 profiles. The data are represented by the gray circles. The dashed line is the best fitting model with constant M/L; the solid line is the best fitting model with a dark matter halo (see text). The projected kinematics of the input model, without dust attenuation taken into account, are represented by a dotted line.